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Request for grant of a patent

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1. Your reference — P165-GB

2. Patent application number *(The Patent Office will fill in this part)* — 0229927.9 — 24 DEC 2002

3. Full name, address and postcode of the or of each applicant *(underline all surnames)*

   1... Limited
   St John's Innovation Centre
   Cowley Road
   Cambridge CB4 0WS

   Patents ADP number *(if you know it)* — 811387 0001

   If the applicant is a corporate body, give the country/state of its incorporation — England

4. Title of the invention — CURVED ELECTRO-ACTIVE ACTUATOR CONFIGURATION

5. Name of your agent *(if you have one)* — Akram K. Mirza

   "Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*

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6. If you are declaring priority from one or more earlier patent applications, give the country and the date of filing of the or of each of these earlier applications and *(if you know it)* the or each application number

Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*

7. If this application is divided or otherwise derived from an earlier UK application, give the number and the filing date of the earlier application

Number of earlier application	Date of filing *(day / month / year)*

8. Is a statement of inventorship and of right to grant of a patent required in support of this request? *(Answer 'Yes' if:* — YES

   a) any applicant named in part 3 is not an inventor, or
   b) there is an inventor who is not named as an applicant, or
   c) any named applicant is a corporate body.
   See note (d))

Patents Form 1/77

9. Enter the number of sheets for any of the following items you are filing with this form. Do not count copies of the same document

Continuation sheets of this form	0
Description	13
Claim *(s)*	2
Abstract	1
Drawing *(s)*	8

10. If you are also filing any of the following, state how many against each item.

Priority documents	
Translations of priority documents	
Statement of inventorship and right to grant of a patent *(Patents Form 7/77)*	
Request for preliminary examination and search *(Patents Form 9/77)*	
Request for substantive examination *(Patents Form 10/77)*	
Any other documents *(please specify)*	

11. I/We request the grant of a patent on the basis of this application.

Signature

Date 24-DEC-2002

12. Name and daytime telephone number of person to contact in the United Kingdom Akram K. Mirza 01223-422290

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Notes

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CURVED ELECTRO-ACTIVE ACTUATOR CONFIGURATION

FIELD OF THE INVENTION

This invention relates to curved elements of electro-active material. More particularly, it relates to a specific configuration of a twice-coiled or super-helical electro-active actuator.

BACKGROUND OF THE INVENTION

Electro-active materials are materials that deform or change their dimensions in response to applied electrical conditions or, *vice versa*, have electrical properties that change in response to applied mechanical forces. The best-known and most used type of electro-active material is piezoelectric material, but other types of electro-active material include electrostrictive material.

Many devices that make use of electro-active materials are known. The simplest piezoelectric device is a block of pre-poled, i.e., pre-oriented, piezoelectric material activated in an expansion-contraction mode by applying an activation voltage in direction of the poling.

Because piezoelectric devices are capacitive in nature, they exhibit a number of desirable mechanical and electrical characteristics. They have an efficient coupling of energy from applied charge to mechanical strain, leading to a high bandwidth, a large force output and negligible resistive heating. Due to their capacitive nature, these devices draw their least current at zero rate of displacement. The electro-active material, which in general is crystalline, ceramic or polymer-based, determines the stiffness of electro-active devices. However, as the electro-active effects are extremely small, e.g. in the order of 0.1 nm/(V/m), the change in

dimensions is relatively small and requires high voltages for thick material sections. Therefore, more complicated electro-active structures have been developed to achieve larger displacements.

To increase the displacements, several designs have been introduced such as stacks, unimorph or bimorph benders, recurved benders, corrugated benders, spiral or helical designs.

Benders, stacks, tubes and other electro-active actuators are employed in a wide array of engineering systems, ranging from micro-positioning applications and acoustic wave processing to printing applications. Generally, actuators are used in such applications to generate force and effect displacement, for example, to move levers or other force transmitting devices, pistons or diaphragms, to accurately position components, or to enable similar system functions. Actuators employed for such functions are typically designed to provide a desired displacement or stroke over which a desired force is delivered to a given load.

Depending upon design, electro-active actuators can generate a rotational or translational displacements or combinations of both movements.

Comparably large translation displacements have been recently achieved by using a helical structure of coiled piezoelectric tape. Such twice-coiled or "super-helical" devices are found to easily exhibit displacement in the order of millimetres on an active length of the order of centimetres. These structures and variations thereof are described, for example, in the published international patent application WO-0147041 or by D.

H. Pearce et al in : Sensors and Actuators A 100 (2002), 281 - 286.

These structures are ceramic devices of complex curved shape.

Whilst these recent electro-active actuators are generally satisfactory for many applications, it was found that an unconstrained object when driven by such a twice-coiled or super-helical actuator may deviate from a desired straight line. In addition the object may rotate slightly. These deviations limit the applicability of super-helical devices in certain technical fields, such as loudspeaker drive unit or lens motors, where strict linearity is a preferable requirement.

Though this undesired motion could be limited by mechanical constraints, the present invention sets out to reduce the above described deviations in the motion of the actuator through changes in its arrangement and configuration.

SUMMARY OF THE INVENTION

According to an important aspect of the invention, there is provided an electro-active device having a structure of electro-active material extending around a minor axis which is permanently curved and wherein the structure of electro-active material includes successive electro-active portions having electrodes to bend, when activated, around the minor axis. A device according to the present invention includes at least two curved sections or, in other words, two twice coiled or super-helical sections, coupled by a joint point or section at which the curvature of the minor axis changes from inward bowing (concave) to outward bowing (convex). In a more

mathematical description, the curvature of the minor axis changes its sign when applying the right hand rule to determine the orientation of the curvature along the minor axis from one end of the device to the other.

In a preferred variant the first and second sections are essentially identical such that deviations from a straight linear motion of moving ends of the device balance each other out, and so cancel each other. To do this effectively the device are driven by essentially identical control signals or voltages. Essentially identical means the devices have the displacement versus applied voltage properties so as to not hamper each other straight-line motion but being capable of balancing out other components of the displacement, notwithstanding immaterial differences or inadvertent variations due to manufacturing tolerances or the like.

In a preferred embodiment the two curved sections are formed from a continuous tape. In a variant of this embodiment the joint section is a small portion of the tape and the device has thus the form of the letter "S".

Alternatively the joint section may be a coupling element or joint section providing connection points to two or more essentially identical sections. To balance each other out, the two or more identical sections are preferable arranged into groups with a rotational symmetry about an axis through the coupling element. These groups could be pairs or triplet or any higher-order arrangement of essentially identical electro-active sections. Two or more groups of section that are internally balanced out, may be arranged in different spatial orientations, for example such that the plane of a first balanced group is perpendicular to a second of such balanced group.

By making the coupling element or joint section flexible in the desired direction of motion but stiff in other directions, the maximum useable linear displacement of the jointed two sections may be increased.

In a particularly preferred embodiment the number and the radius of windings around the minor axis are chosen such that the joint section and the two unconnected ends are located at opposite circumferential positions. This orientation facilitates the mounting and use of the device on a flat surface such as a printed circuit board (PCB).

The present invention is particularly advantageous for use as loudspeaker drive unit or lens drive system.

These and other aspects of inventions will be apparent from the following detailed description of non-limitative examples making reference to the following drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings:

FIG. 1 is a perspective view of a twice-coiled actuator as known;

FIG. 2 shows an example of an actuator in accordance with the present invention;

FIG. 3 shows the example of FIG. 2 as drive unit for a center-mounted loudspeaker cone;

FIGs. 4 A, B shows a further example of an actuator in accordance with the present invention;

FIG. 5 shows another example of an actuator in accordance with the present invention;

FIG. 6 shows another example of an actuator in accordance with the present invention; and

FIG. 7 shows another example of an actuator in accordance with the present invention.

DETAILED DESCRIPTION

In FIG. 1, there is shown a known actuator of the twice coiled or super-helical type described in the above-mentioned WO-0147041 and Sensors and Actuators A 100 (2002), 281 -286.

The actuator **10** has a curved portion **12** of bimorph tape **11** that is wound helically around a first axis **13** referred to as the minor axis. For illustration, the minor axis is shown as a dashed line in FIG. 1. The helically wound portion is further coiled into a secondary winding of about three quarters of a complete turn. The axis **14** of this secondary winding is referred to as the major axis and shown as a small dashed circle with a central solid point again to facilitate description and illustration. The first winding is known as the primary winding or primary helix. The secondary winding could exceed one turn and form a spiral or secondary helix. It is therefore usually referred to as secondary helix, even though shown in the examples herein as three-quarter winding only.

When poled and activated as described in the above references the distal free end **111** moves parallel to the major axis **14** and thus perpendicular to the paper plane assuming that the base-mounted or near end **112** is fixed to an immobile support **15**.

As the displacement of the distal end represents a motion caused by summing infinitesimal rotational and bending displacements of the tape **11** around the minor axis **13**, it is not surprising that its motion is not strictly linear in the sense of moving in a straight line but comprises small rotational components. These deviations from a straight line are acceptable in many applications and can be limited by further mechanical constraints such as bearings.

The present invention improves the straight-line motion of the known actuator of FIG. 1 by coupling one or more of the known actuators as balanced pairs, triplets, quadruplets etc. of essentially identical actuator sections into a configuration arranged such that at least some of the non-linearities of the known actuator are balanced out and hence reduced or eliminated from the motion of the free end of the combined actuator.

As the piezo-ceramic tape undergoes many manufacturing steps from the formulation of the base powder including tape casting, electroding, winding, firing and poling, all of which could potentially introduce variations and inhomogeneity between single actuators, it is advantageous to manufacture the balanced stes of actuator sections from a single continuous tape. Thus in a first example of an actuator in accordance with the present invention, a balanced pair is formed from a continuous tape of electro-active ceramic material.

The novel actuator **20** of FIG. 2 has a first section **201** and a second section **202** coupled by a small joint section **203** that is the twist or winding along which the orientation of the curvature changes. The two sections are formed as the known actuator described with reference to FIG. 1 above and, hence, like reference numerals are used to denote like elements. Both sections include a curved portion of bimorph tape **21** that is wound helically around a first axis that is referred to as minor axis. The helically wound portion is further coiled into a secondary winding of about two-thirds of a complete turn.

However, the first section **201** is bent inwardly thus giving the first section concave curvature. In the joint section **203** the curvature is reduced and approaches zero before the minor axis bends outwardly in the part of the helically wound tape that forms the second section **202** of the actuator.

The device of FIG 2 exhibits a symmetry about the joint section that could be described as being point-symmetric. It is therefore arbitrary to define the first section as concave and the second section as convex. It is however important to notice that the curvature changes its sign or orientation from one section to the other. A sign or orientation can be assigned to a curvature by use of the so-called right hand rule, following which, as the fingers are curled as the device, the thumb defines its orientation. Applying this rule at each point of the device from one end to the other the orientation flips after passing through the joint section. The major axes **241**, **242** of the first and second sections **201**, **202**, respectively, are illustrated in FIG.2, with a point in a dashed circle marking an orientation out of the paper plane and cross in a dashed circle marking the opposite orientation

taken by passing from the left to the right end of the actuator.

The number of primary windings is six for each section of the actuator. The thickness of the tape is 1.2 mm. Its width is 5.5 mm. The outer diameter of the primary helix is 5 mm and the outer diameter of the secondary helix, which is a 0.75 turn, is 30 mm. Each section includes an additional half turn that makes up the joint section **203** of the actuator. The tape has a linear piezo constant of 135 pC/N. Such a bimorph tape device can be driven by a 600 Volt amplitude signal to a maximal displacement of 0.5 mm. In a device with 8 active layers of piezoelectric material the same displacement can be achieved with a drive voltage of 150 V.

The flat plateau part of the joint section **203** is located at a circumferentially opposite position of both the end parts of the first and second section. This arrangement facilitates the mounting of objects to be driven or actuated by the novel actuator, as shown in FIG. 3 illustrating a loudspeaker configuration.

In FIG. 3, the actuator **20** of FIG. 2 is shown driving an oval shaped cone **30**. The cone is the sound-generating element or the diaphragm of a loudspeaker system. The flange **31** of the cone is connected to the mounting plate **35** of the actuator through four struts **32**. The actuator **20** rests on two flat mounting posts **351** above the mounting plate **35**. At its centre, the joint section **203** and the apex **33** of the cone are connected. Alternatively, the mounting points could be reversed, using the central joint section to mount the actuator onto the immobile base and connecting the object to be moved to one or both ends of the actuator.

In operation the device of FIG. 3 is driven with a drive voltage of up to +/- 600 V peak voltage modulated with frequencies within the acoustic frequency range of 20 Hz to 20 kHz.

The actuators of FIGs. 2 or 3 can be made using the manufacturing steps known for producing super-helical device (as shown in FIG. 1). The manufacturing process starts using a commercial piezoelectric lead zirconate titanate (PZT) powder as the base material, for example TRS 600 (TRS Ceramics Penn., USA). The powder is mixed with polyvinyl butyral binder and cyclohexanone on a twin-roll mill until a uniform 1 mm thick sheet is obtained. This material is then rolled up and extruded to obtain a uniformly thick and defect-free sheet. The sheet is then calendered to the required thickness being half of that of the final bimorph tape.

The bimorph structure is produced by screen printing the tape with conductive ink such as platinum ink. Two or more of these tapes can then be laminated to form bimorphs. Strips of suitable width are cut from the tape and wound on to a first cylindrical former the outer diameter of which determines the inner diameter of the primary helix. The strips are then placed into a second former that determines the secondary helix shape and radius. The second former has an S-shaped groove having a depth in the order of the diameter of the primary helix.

The assembled structure is then dried to remove solvents and plasticisers. At this stage support for the projecting terminal may not be necessary as the structure becomes sufficiently rigid to not collapse under its own weight. The actuator is then fired: Following a slow binder removal stage

up to 600 degrees C, the material is sintered at 1200 degrees C for 1 hour.

Soldered electrode contacts are made to the outer two electrodes and the single inner electrode. The material is poled in a heated silicone oil bath at 120 degrees C and 2.5kVmm-1 for 10 minutes. After cleaning, the outer two electrodes are joined together to form a single external electrode and the central electrode is used to generate the required opposing actuation fields.

In other examples of the invention the novel actuator **40** is assembled by joining two actuators as known per se and illustrated in FIG. 1 through a joint element or hub of hetero (non-piezoelectric) material such as metal or plastics. In FIG. 4, the joint element is a steel flexure **403**. The flexure is designed to be stiff in lateral directions while being more flexible in the vertical (out of the paper plane of FIG. 4A). The actuator further includes two three-quarter turn super-helical actuators **401, 402** bonded at their respective distal ends by a glue or adhesive or other suitable attaching technique to the joint element **403**.

In this configuration the actuator can exhibit a larger displacement with albeit less force than the example described above.

In FIG. 4B the device **40** is shown with both actuator sections **401, 402** bent upwards. The displacement causes the joint element **403** to flex. In applications where such a flexing action is not desired, the flexure could be replaced with a stiff bridge element with or without hinges at the joining lines with the two actuators, or with a single hinge at the center of the joining piece.

The configuration of FIG. 4 can be extended to multi-turn sections where each actuator section has several turns around its major axis before being joined.

Alternatively, the two actuators section may be nested. In FIG. 5 the free ends of each section **501**, **502** are located within the inner circumference of the other section, thus providing a more compact configuration of the novel actuator. The elements and structures in FIG. 5 are otherwise identical to those of FIG. 4 and are, hence, not further described.

In another variant, there are more than two actuator sections joined in a manner that maintains the required balance between the undesired displacements. A possible configuration of such an actuator is shown in FIG. 6. The actuator combines two balanced pairs of actuator sections **601**, **602** joined by a central cross-shaped hub or joint element **603**. The elements and structures in FIG. 6 are otherwise identical to those of FIG. 4 and are, hence, not further described.

In another variant, there are three actuator sections joined in a manner that maintains the required balance between the undesired displacements. A possible configuration of such an actuator is shown in FIG. 7. The actuator **70** combines three actuator sections **701**, **702**, **703** joined by a central cross-shaped hub or joint element **704**. The desired cancellation of non-straight-line motions will occur so long as the actuator sections are placed symmetrically about the central joining element, in this example at radial positions each separated by 120 degrees.

It will be apparent that more complex groups of balanced actuator section can be arranged to form the novel actuator.

And several groups of actuators may be arranged in differently oriented planes such that the direction of the straight-line motion is the (vector) sum of the motion generated by the actuator sections within each group.

P165-GB

CLAIMS

1. An electro-active actuator adapted to move objects in a straight line, said actuator having at least one group of coupled actuator sections with each of said sections having a structure of electro-active material extending around a minor axis which is permanently curved and wherein the structure of electro-active material includes successive electro-active portions having electrodes to bend , when activated, around the minor axis, and said sections being coupled by a joint element and arranged in a rotational symmetry about said joint element.

2. The actuator of claim 1 wherein the actuator sections within group move, when activated, parallel while balancing out motions in other directions.

3. The actuator of claim 1 wherein the actuator sections within each group are essentially identical.

4. The electro-active device of claim 1 wherein each section comprises a continuous electro-active element extending along and curving around the minor axis.

5. The electro-active device of claim 1 wherein each section comprises a continuous electro-active element extending along and curving around the minor axis as a helix.

6. The electro-active device of claim 3 wherein each section comprises a continuous electro-active tape extending along and curving around the minor axis.

7. The actuator of claim 1 having at least one inwardly curved actuator section and at least one outwardly curved actuator section coupled by the joint section.

8. The actuator of claim 7 wherein the inwardly curved actuator section and the outwardly curved actuator section are formed from one continuous tape of electro-active ceramic material.

9. The actuator of claim 8 wherein the first and second section forming the pair and the joint section are formed from one continuous tape of electro-active ceramic material being wound around an minor axis curved into an "S"-shape.

10. The actuator of claim 1 wherein the joint section comprises a hetero material.

11. The actuator of claim 10 wherein the joint section is adapted to be stiff in all but a preferred direction.

12. The actuator device of claim 1 wherein all actuator sections within one group are adapted to receive essentially identical activation signals.

13. An actuator constructed and arranged to operate substantially as hereinbefore described hereinbefore with reference to the accompanying drawings.

F165-GB

ABSTRACT

Curved electro-active devices are described comprising actuator sections being symmetrically arranged and balanced in a preferred direction and thus generating an improved linear straight-line displacement for objects such as loudspeaker diaphragms or lenses.

65-GB

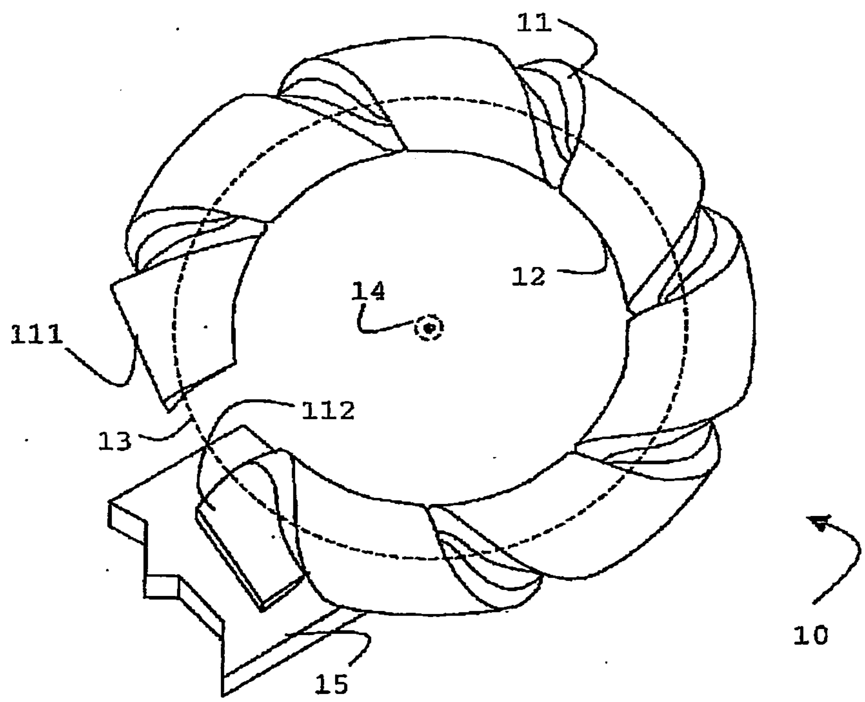

FIG. 1 (Prior Art)

65-GB

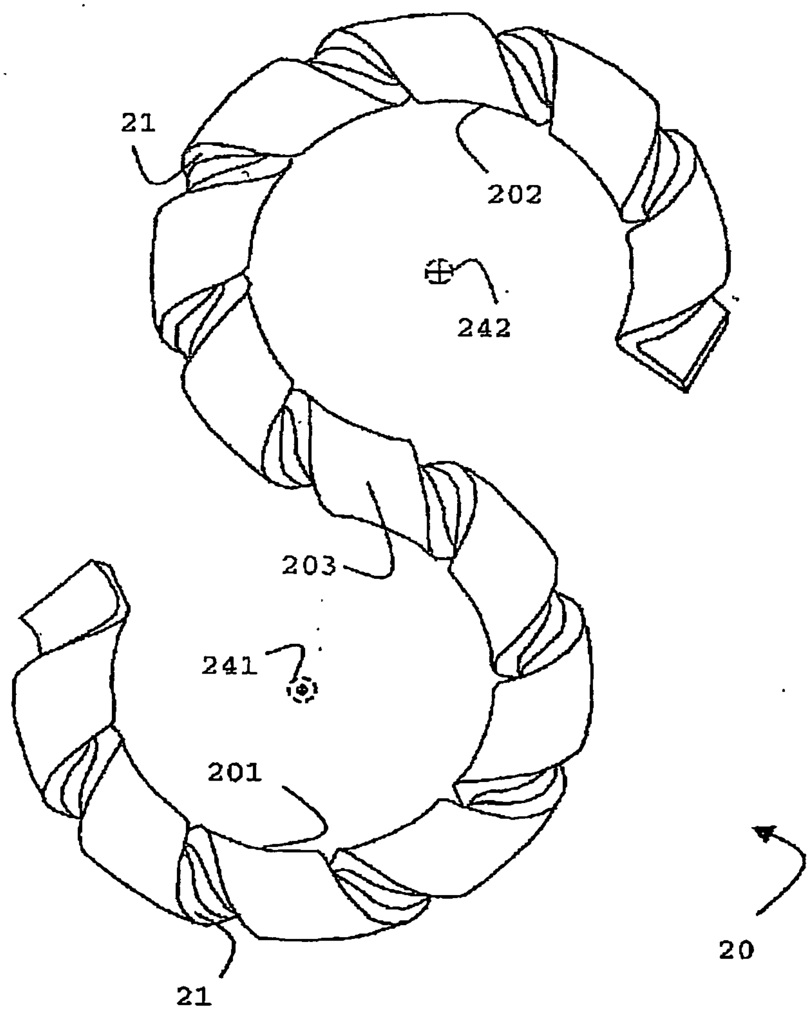

FIG. 2

5-GB

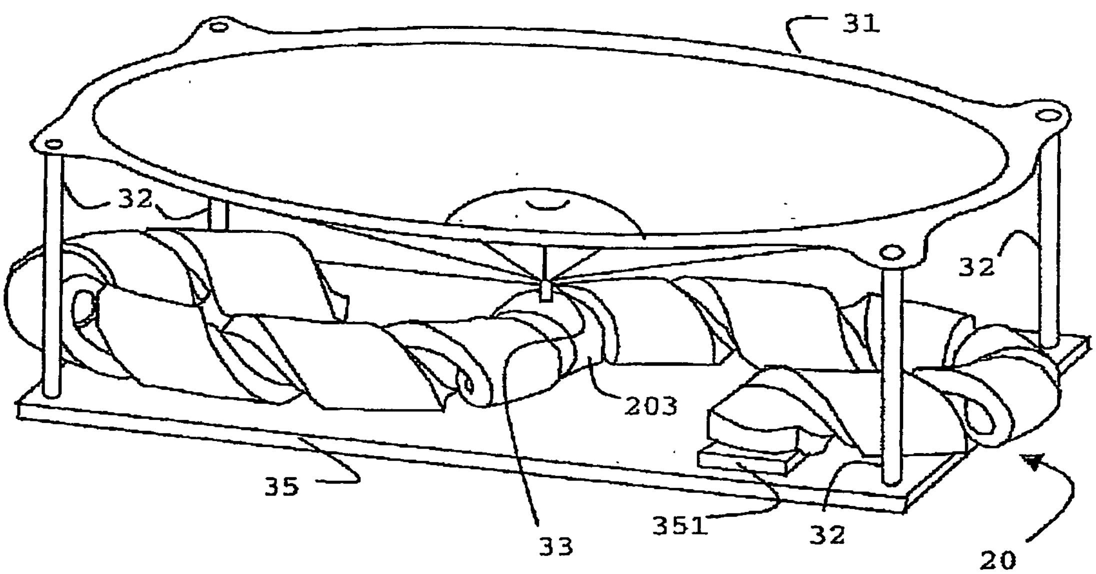

FIG. 3

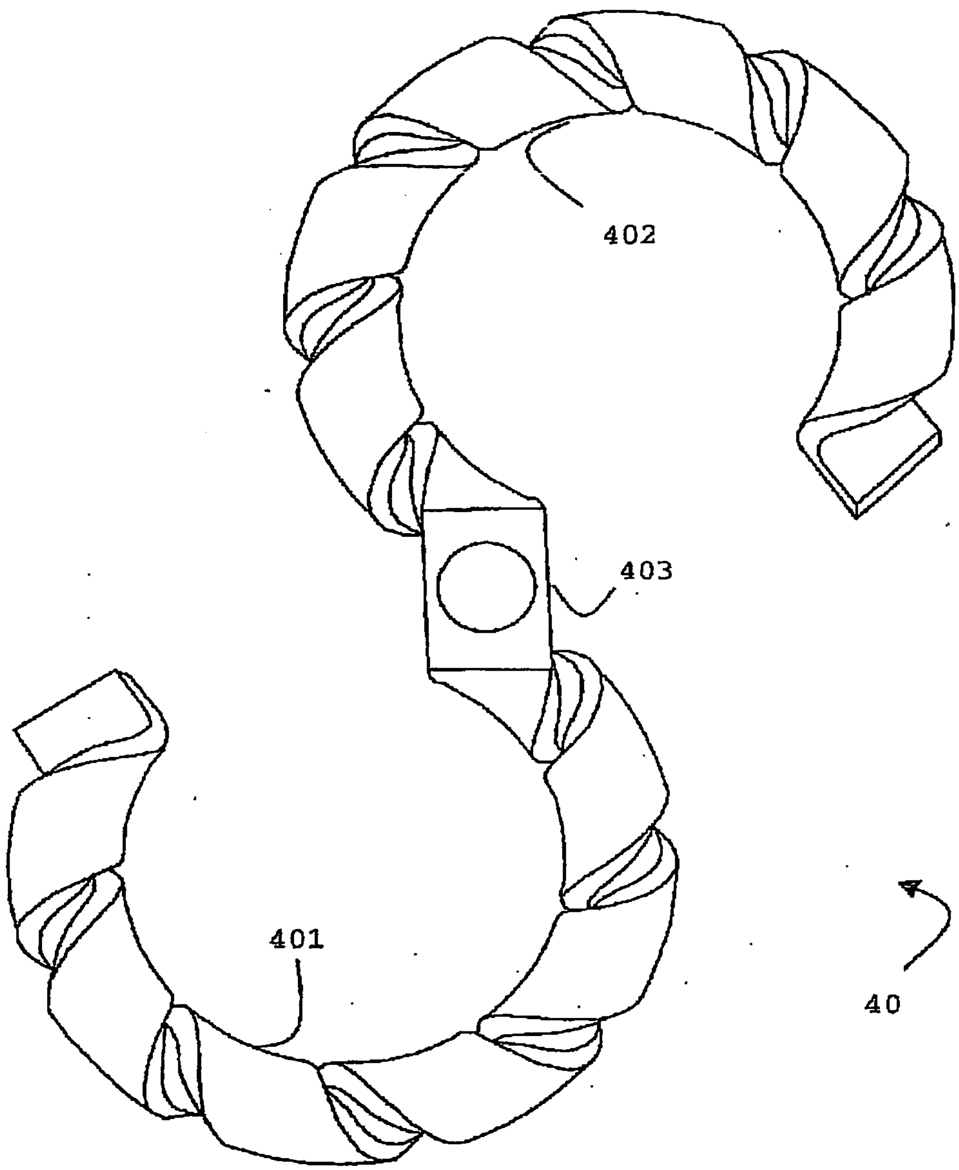

FIG. 4A

65-GB

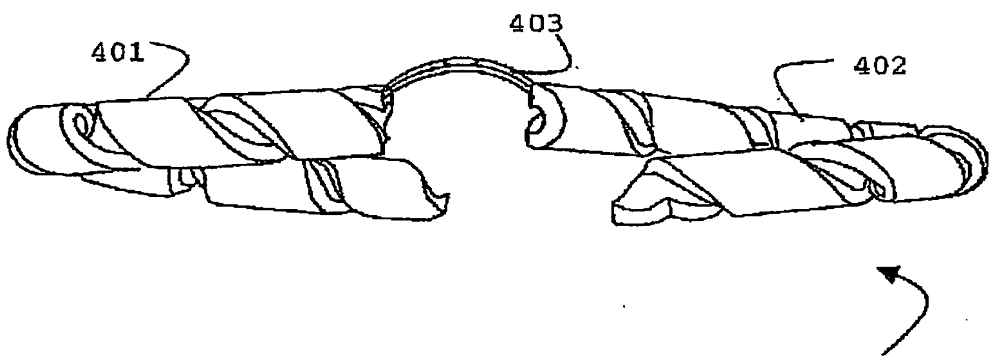

FIG. 4B

65-GB

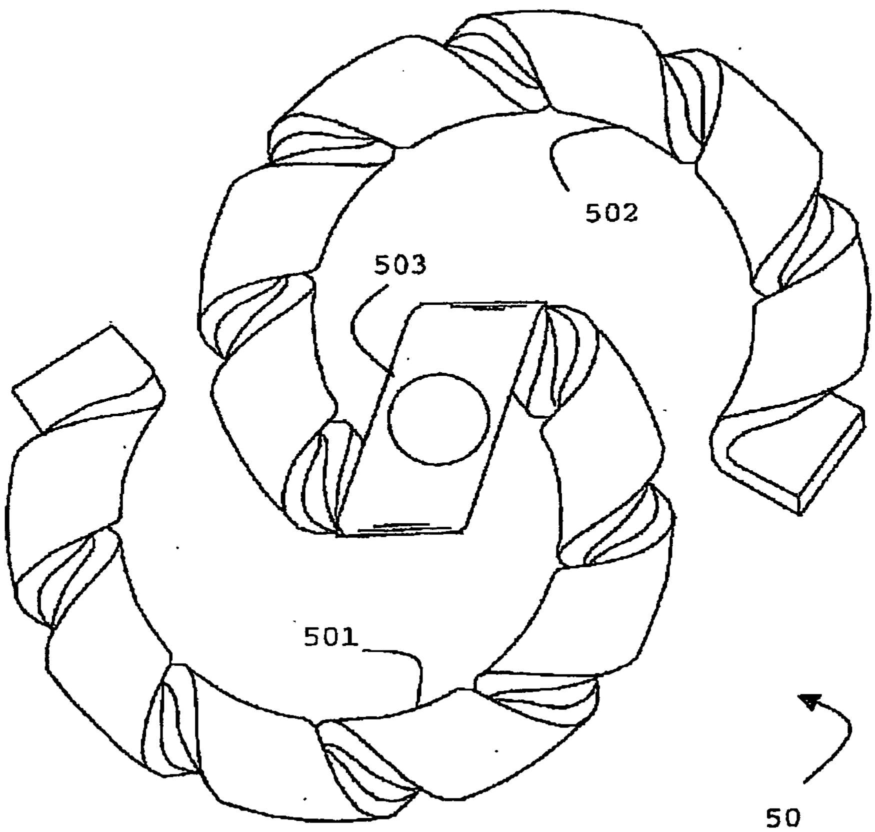

FIG. 5

65-GB

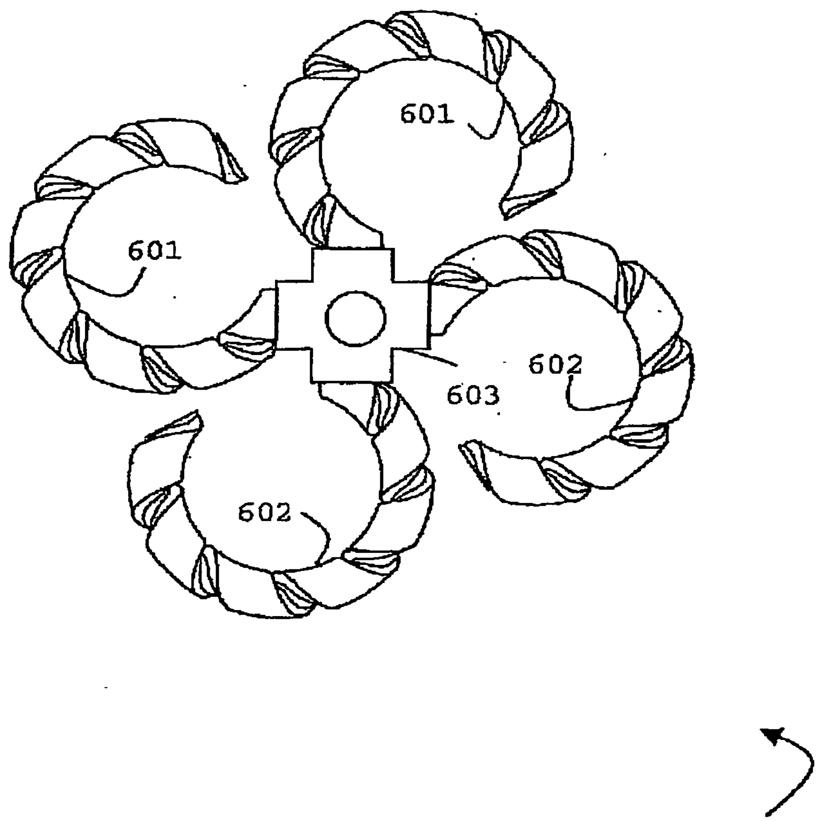

FIG. 6

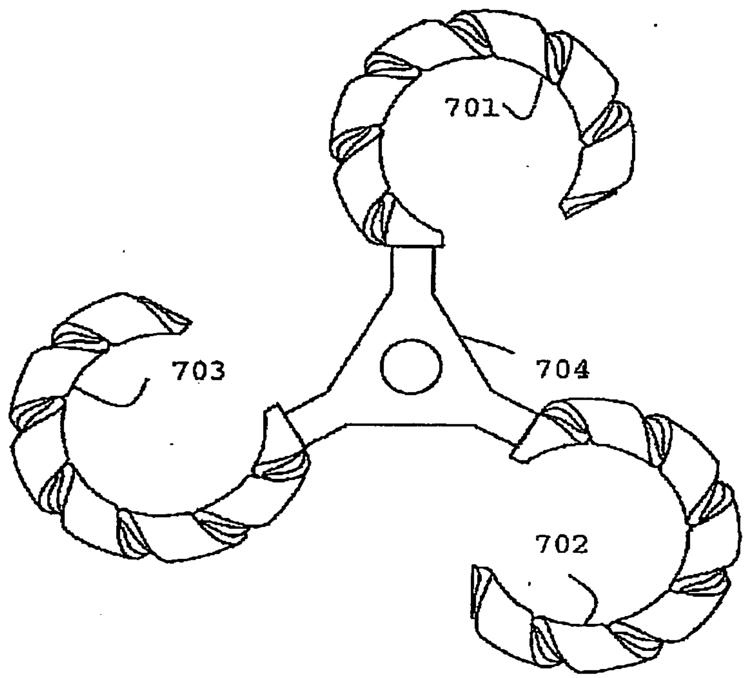

FIG. 7